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TECHNOLOGY IN GROWTH

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ABSTRACT

Technology in Growth*

We review the role of R&D in endogenous growth theory, and describe extant empirical research – macro and micro – bearing on R&D as an engine of growth. Taking R&D to be key, while recognizing the significance of economic incentives, emphasizes knowledge as an economic object and, more generally, the economics of intellectual property rights. This paper argues that property rights matter, but in subtle counterintuitive ways, not yet fully investigated in research on endogenous growth.

JEL Classification: D90, O30, O33
Keywords: endogenous growth, innovation, intellectual property rights, ideas, knowledge, patents, R&D, spillover

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NON-TECHNICAL SUMMARY

This paper reviews the role of research and development (R&D) in endogenous growth theory. It describes the existing empirical research that bears on R&D as an engine of growth.

How to alter the underlying growth trend of an economy is a policy question that confronts all modern societies. One widespread view is that, for those economies identified as less developed, growth can take place by learning from or copying those more advanced. For the latter, however, no such option is available. Only by pushing the envelope of knowledge or technology can these already-advanced economies continue to grow. Since R&D is the most immediately visible mechanism by which technology can be thought to progress, it must therefore be the engine of growth in the advanced economies. More R&D leading to raised levels of technology must therefore be good for economic growth.

This reasoning is appealing and seductive. It calls for theoretical modelling to clarify the mechanism by which R&D translates into improved technology and then to increased growth. Without this, we cannot understand the incentives that drive economic actors to do less or more R&D; we cannot investigate whether outcomes are socially efficient. At the same time, the reasoning calls for empirical analysis to assess the connections between R&D, direct measures of its accumulated outputs, and ultimately aggregate economic growth.

Our first key conclusion can be stated simply in the following set of related statements.

1. All analyses recognize that technological progress (or, its concrete manifestations, accumulated stocks of R&D) is an important engine of growth.

2. All analyses acknowledge the significance of economic incentives for determining growth outcomes.

3. Knowledge is the accumulation of R&D output, broadly interpreted.

It follows, as a matter of logic from these observations, that the economics of knowledge must underlie appropriate policies for growth. In this view, the rights accorded intellectual property become central. What is far from settled,

though, are questions concerning the efficiency, desirability and precise nature of alternative systems of intellectual property rights.

Intellectual property rights, we argue, should be taken to mean not only patents or copyrights. Instead, a broader notion – including, among other things, trade secrets, lead time, or even just the process of learning by doing – is more useful. In this expanded view, it might be altogether irrelevant to take into account the conventional trade-off between, on the one hand, the *ex-ante* private incentives for individual agents to create knowledge and, on the other hand, the *ex-post* social inefficiency in preserving private monopoly on that created knowledge. Alternative institutions, such as patronage and procurement, also have optimality properties under particular economic environments. Moreover, historical examples of these alternatives have existed in the real world, and continue to do so. In the same vein, we argue that it is not insightful to view knowledge accumulation or technological progress as deriving from just private-sector R&D.

We have organized the paper's discussion of the empirical evidence to parallel that of the theoretical research. We evaluate the evidence along three broad hypotheses:

1. The positive relation between technology growth and the quantity of resources devoted to improving technology (traditionally taken to be the resources used for private-sector R&D);

2. The appropriateness of using an aggregate stock of patents (weighted or unweighted) to proxy the multi-dimensional attributes in technology;

3. The public availability of the current state of technology for further research, when in principle that technology is protected only for owner use in production.

We conclude that the empirical evidence provides some support, although not enthusiastically, for 1 and 3. Instead, the data speaks more strongly and more interestingly on caveats and subtleties in 1 and 3, and do not merely endorse or reject the hypotheses outright. On 1, the data do show correlations between individual firm R&D and patents, and also between both R&D and patents, on the one hand, and firm performance measures, on the other. The correlations do not, however, systematically confirm simple mechanisms at the aggregate level between research resources and economic growth and macroeconomic performance.

On 3, the empirical evidence suggests that knowledge spillovers do occur. They are, however, concentrated in spatial, industrial, and political clusters and flow only through specific mechanisms (e.g. trade imports). This runs counter to theoretical predictions, arising from the intrinsic properties of knowledge.

Finally, in our judgement, the empirical evidence refutes 2. Most telling for this are the survey results that find product and process patents to be less effective than practically any other form of intellectual property protection. Lead time, moving down the learning curve, secrecy and sales or service specialization are all routinely viewed to better protect economically valuable ideas.

Moreover, a significant fraction of R&D is carried out by other than profit-seeking private agents. In 1996, government-funded R&D accounted for between one-third and one-half of total R&D expenditures in the United States and Europe: In Germany, 37%; United Kingdom, 32%; United States, 34% and France and Italy, approximately 45% in each.

The important difference between private and public R&D is not what is researched, but instead the incentives of the researchers involved. Understanding the macroeconomic and growth implications of this is not straightforward but, we think, important.

The caveats and cautions we describe in the paper are meant to be constructive. They point to further research necessary for properly understanding the role of technology in economic growth.

1 Introduction

This paper reviews the main insights from the theoretical R&D endogenous growth literature, and summarizes empirical counterparts to that theoretical work.

A key conclusion can be simply stated in the following set of related statements.

1. All analyses recognize that technological progress (or, one concrete manifestation, R&D) is an important engine of growth.
2. All analyses acknowledge the significance of economic incentives for determining growth outcomes.
3. Knowledge is the accumulation of R&D output, broadly interpreted.

It follows that the economics of knowledge must underly appropriate policies for growth. In this view the rights accorded intellectual property become central. However, the efficiency, desirability, and precise nature of alternative systems of intellectual property rights comprise issues that are far from settled.

Within this broad agenda, the literature has instead emphasized only private-sector R&D and patents, respectively, as the forms of invention and rewards. As we see it, this focus has arisen for four reasons:

- Tools for modelling private sector behavior are well-developed.
- Data on R&D and patents exist to motivate and test hypotheses on growth.
- R&D is a readily-identifiable factor input for knowledge production in many technology-driven industries.
- Patents are a readily-identifiable if imperfect measure of knowledge output.

Economics focuses on the incentives that confront private individuals and firms. The endogenous growth literature follows this tradition in modelling technological progress to result largely from incentives facing profit-maximizing firms. In the theoretical literature firms in the private sector fund and carry out R&D: this, in turn, is the paradigm typically examined in empirical work.

Such a focus might seem excessively narrow. However, this "private R&D with patents" scenario has developed through a series of sensible decisions. Each step along the way applies the traditional tools of economic analysis—optimizing behavior and equilibrium outcomes. Where the reasoning becomes subtle, however, is that R&D output—accumulated knowledge—is infinitely expansible (see below): It can be used by many without itself being drawn down, and thus has some of the nature of a public good.

But firms perform R&D only if they can appropriate the rents from it. The mechanism for such appropriation is typically assumed to be patenting which, in concept, also simultaneously reveals the patent information to all other interested agents. That knowledge, although revealed, is then protected in that only its owner can use it to produce final output. The information in the patent, on the other hand, can be used for additional R&D by rival firms. This allows the infinite expansibility of knowledge to generate increasing-returns effects on the economy overall.

Patent data are plentiful and, at face value, reliable. The empirical literature has therefore been able to exploit the substantial micro- and macro-level data on R&D and patenting. Patents and R&D proxy knowledge production-function outputs and inputs, and can therefore be used in empirical production function analyses. The theoretical literature has, in turn, used those empirical findings to motivate and justify alternative modelling strategies.

As we discuss below, this private-sector R&D-patenting model is highly pertinent for certain industries. In so far as this description of knowledge accumulation is adequate, the theoretical and empirical literatures provide credible specific policy recommendations. However, many important forms of knowledge accumulation fall outside this paradigm.

The rest of this paper is organized as follows. Section 2 relates insights from early growth models to those from more recent R&D-driven endogenous growth models. Towards the end of the section we discuss some broader questions on economic growth and knowledge as economic property: Research here is thin and, we argue, has thus far failed to deliver concrete conclusions.

Section 3 summarizes some of the principal results from empirical work examining the effects of R&D and patents on economic performance of both firms and the aggregate economy. We relate the micro and macro findings to key features of the knowledge accumulation process in R&D-driven endogenous growth theory. Some of these latter are consistent with empirical findings. Others are not.

Our conclusions from this survey of R&D and economic growth are as follows. We see a continuing need for theoretical and empirical research in this area. While the private-sector R&D/patent framework provides essential groundwork, it has, in our analysis, important limitations. Most knowledge accumulation does *not* occur from private firms' R&D producing patentable knowledge. Nor is it clear that the institutional mechanisms producing and demanding knowledge more broadly are well understood.

2 Development of the literature

Robert Solow's [71] analysis of economic growth—with its emphasis on income being driven by transitional dynamics in capital—is so influential and far-reaching that many take physical capital accumulation to be *the* defining feature of neoclassical growth theory. Following quickly from this is the suggestion that neoclassical theory asserts capital accumulation is the principal engine of economic growth.

The observed cross-country variation in savings rates and per capita incomes refutes this suggested importance of physical capital (e.g., Lucas [55], Romer [64, 66]). If one maintains that physical capital accumulation is the main source of variation in incomes, then—under plausible calibrations of key parameter values—savings rates in the rich developed economies should be orders of magnitude larger than those in the poor developing economies. That predicted range turns out to be greater by far than the observed range in reality. This inconsistency has been used to argue that neoclassical theory provides no credible guide to understanding economic growth. Instead, technological progress and its determinants are deemed central.

2.1 Origins

Early on, however, researchers in the neoclassical tradition were already documenting the importance of technological progress in economic growth.[1]

After noting real US net national product per capita grew four-fold between 1869–78 and 1944–53, Abramowitz [1] concluded:

> "The source of the great increase in net product per head was not mainly an increase in labor input per head, not even an increase in capital per head ... Its source must be sought principally in the complex of little understood forces which caused productivity, that is, output per unit of utilized resources, to rise."

Kendrick [51] considered US economic performance from 1899 to 1953, and concluded that total factor productivity (TFP) explained 53% of the growth in real aggregate output over that half century. Solow's own study [72] showed technical change accounted for $87\frac{1}{2}\%$ of the growth in US gross output per manhour over 1909–49.

This sample of findings is, moreover, no artifact of hindsight sample selection.[2] Indeed, its message is how Arrow [6] begins a classic 1962 article:

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[1] An important difference between more recent empirical studies and these published in the mid 1950s is that the latter focused almost exclusively on time-series evidence for a single country, while more recent ones, exploiting studies such as Maddison [56] and Summers and Heston [74], exploit variation across countries as well (Durlauf and Quah [23]).

[2] To be clear, our goal is not to claim this is the last word on TFP measurement. Far from it: We intend simply a summary statement on the then-extant state of knowledge in neoclassical growth research. We do not mention, for instance, the large literature following Jorgenson and Griliches [48] that examines quality adjustments in factor inputs (although it seems to us that, conceptually, adjusting for quality cannot show technology to be unimportant—what is quality after all but technology?). The tabulation given in Barro and Sala-i-Martin [9, Table 10.8] shows it is the more recent empirical research that has downplayed the importance of technological progress, although admittedly TFP's contribution to growth remains large.

> "It is by now incontrovertible that increases in per capita income cannot be explained simply by increases in the capital-labor ratio."

By 1969 the economics literature on technology and growth had progressed to where a collection of papers (Stiglitz and Uzawa [73]) identified the following issues:

1. What determines the rate of technological progress? [Is it purposeful, or is it only incidental to some other deliberate investment, say, physical capital accumulation? What government policies influence it?]
2. Does technological progress affect different factors differently? (Are certain kinds of technical change labor-saving? Capital-saving? [Biased against labor of different skill levels?]) What economic factors determine the differential effects if any?
3. How does new technology manifest in the economy? Is technology embodied in physical capital according to different vintages? [How does new technology affect the productivity of older capital and earlier investment?]

These questions remain the subject of intense and active research in the present.[3]

It is striking how these questions (by 1969!) bear phrasings that deny a sharp distinction between "old" and "new" growth theories. Under one (not especially generous) interpretation, recent theories of growth simply carry

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It seems that what many now consider the neoclassical preoccupation with physical capital accumulation for growth is the *opposite* of what researchers then actually thought. Instead, that imputed preoccupation follows only more recent empirical analyses. At the same time, however, it is the more recent theoretical work on endogenous growth that emphasizes the importance of technical progress.

[3] The questions in square brackets might not be exactly as expressed in the early papers, but are issues still being researched that are certainly not out of place relative to the others found here.

forward, in different guises, the insight that technical progress is endogenously determined in economically interesting ways. Early growth theorists certainly were aware that technical progress might not be exogenous. As in the old joke about economics examinations, it seems that the fundamental questions have for long remained the same; only the answers have changed.[4]

2.2 The neoclassical mechanism

One can strip away the long-familiar emphasis on physical capital accumulation, and reinterpret the formalism of Solow's [71] neoclassical framework in a way consistent with the time-series empirical observations just described (and, indeed, cross-sectional as well).

Let $y_j(t)$ and $k_j(t)$ denote, respectively, output and capital per worker in economy j at time t:

$$y_j(t) = Y_j(t)/N_j(t) \qquad k_j(t) = K_j(t)/N_j(t),$$

with Y_j and K_j the corresponding aggregate quantities, and N_j the total number of workers. Write $A_j(t)$ for the state of technology in j at t, and suppose that output and capital are related by the production function

$$Y_j = F(K_j, N_j A_j) \implies y_j = F(k_j, A_j) = A_j f(k_j/A_j), \tag{1}$$

where, by the notation, F is homogenous of degree 1. Assume the worker-intensive production function f satisfies

$$f' > 0, \; f'' < 0, \text{ and } \lim_{k \to \infty} f(k)k^{-1} = 0, \tag{2}$$

and is common across economies.

Let N_j and A_j evolve, respectively, as:

$$\dot{N}_j/N_j = \nu_j > 0, \qquad N_j(0) > 0, \tag{3}$$

$$\dot{A}_j/A_j = \xi_j > 0, \qquad A_j(0) > 0, \tag{4}$$

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[4] For instance, even the most cursory look at the older literature reveals its obsession with the potential instability of the dynamics and with the incipient pathology in defining the production function, neither of which are any longer considered central to economic discussion.

and let physical capital decay at a constant exponential rate $\delta \geq 0$ common across economies. Assume savings is a constant fraction τ_j of total income and transforms into physical capital according to:

$$\dot{K}_j = \tau_j Y_j - \delta K_j, \qquad \tau_j \text{ in } (0,1),$$

so that

$$k_j/k_j - A_j/A_j = \tau_j \frac{f(k_j/A_j)}{k_j/A_j} - (\delta + \nu_j + \xi_j). \tag{5}$$

Equation (3) says the workforce in economy j grows smoothly at rate ν_j. Similarly, (4) says the state of technology or TFP grows at rate ξ_j.

No economic model implies that A_j has to be the same across j. Rather, the standard interpretation of the neoclassical model simply *assumes* so. At this level of reasoning, it is unclear why one assumption—equality of A's across economies—is better than any other. Indeed, one might argue that to clarify precisely this point is one of the purposes of a useful economic model of technology and growth.

Standard reasoning, e.g., Fig. 1, shows that model (1)–(5) displays a *balanced-growth equilibrium* with

$$y_j/y_j = k_j/k_j = A_j/A_j = \xi_j,$$

and thus a steady-state path for output

$$\begin{aligned} \log y_j^*(t) &= \log f\left([k/A]^*\right) + \log A(t) \\ &= \log f\left([k_j/A_j]^*\right) + \log A_j(0) + \xi_j \cdot t \\ &\overset{\text{def}}{=} \Gamma_{j,0} + \xi_j \cdot t. \end{aligned} \tag{6}$$

Outside of balanced-growth equilibrium, output per worker follows a convergent trajectory to its steady-state path (6), i.e.,

$$\log y_j(t) = \log y_j^*(t) + [\log y_j(0) - \Gamma_{j,0}]e^{\lambda_j t}, \tag{7}$$

where

$$\lambda = \lambda(\delta + \nu_j + \xi_j; f) < 0$$

is the *rate of convergence*. In (7) output per worker is driven by two factors: First, technical progress, described in y_j^*, which simply grows at rate $A_j/A_j = \xi_j$. Second, convergence, which when $\log y_j(0) < \Gamma_{j,0}$ produces growth at rate $-\lambda_j$. (Take, for instance, y_2 in Fig. 2.)

An important feature of the growth path (6)–(7) is that given a market for investment that path can be achieved through the competitive mechanism, and, moreover, attains social efficiency.[5]

From Fig. 1 the definition of $[k/A]^*$ as the intersection of the two loci means there is an increasing function g for which

$$\Gamma_{j,0} = g((\delta + \nu_j + \xi_j)^{-1}\tau_j) + \log A_j(0).$$

Fig. 2 graphs some potential timepaths for (7): Note the wide range of behavior that is possible.

Our immediate goal is to reconcile predictions (7) and Fig. 2 with economic growth observations in reality. First, take the evidence on the relative importance of technological progress versus capital accumulation for explaining growth. In (7) the two components $\log y_j^*(t)$ and $[\log y_j(0) - \Gamma_0]e^{\lambda t}$ evolve due to technological progress and physical capital accumulation, respectively. Saying the first is more important than the second is then simply saying that $\log y_j(0)$ is a particular distance from its steady state counterpart Γ_0, or in words, how far the economy is from steady state. In the model technological progress accounts for all of observed growth when $\log y_j(0)$ happens to be exactly at Γ_0. By contrast, if $\log y_j(0) - \Gamma_0$ is sufficiently large, then capital accumulation explains most of the observed dynamics in y_j.

Put differently, using the estimated importance of technological progress—in historical time-series data—to cast doubt on the neoclassical model (1)–(5) is nothing more than taking a stance on how far an economy is from steady state. Without independent knowledge of where steady state is, historical time-series data do not allow us to reject the neoclassical model.

What about the cross-section behavior of incomes? Can the neoclassical model be reconciled with the pattern of incomes and savings rates we observe

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[5] The derivation is so well-known that it hardly needs further elaboration, although different expositions in the literature emphasize different details. Our discussion follows Durlauf and Quah [23].

across economies? Fig. 2 provides one answer. If A_j is permitted to differ sufficiently across economies, then almost any behavior in cross-sectional income dynamics can be accommodated in the model. Arguments that suggest the opposite invariably assume A_j's identical across countries.

The issues just described are hardly substantive economic ones: they will not be resolved by application of economic theory. More to the point, many observers (ourselves included) find unconvincing the reconciliation just offered of empirical evidence and the neoclassical model. The model, when it assumes unrestricted A's and Γ_0's, has too many degrees of freedom to shed light on the importance of technology versus capital accumulation in economic growth. But what should replace the unrestricted (A, Γ_0) assumption? Simply taking the other extreme of requiring A's and Γ_0's to be identical across economies cannot be satisfactory either. Nor do we know how far economies are from steady state—a different question, certainly, from knowing what the rate of convergence λ might be.

To summarize, the problem is not just being able to explain the empirical facts or being able to generate growth in an explicit model. In the model (1)-(5) we cannot discuss the incentives that form A, the economic mechanisms that explain A's evolution through time, and the economic reasons for A_j's distribution across countries. Without knowledge on these, no policy recommendation can pretend to be well-informed. These questions lead us naturally to models of endogenous technological progress.[6]

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[6] A great deal of empirical growth research takes a flexible approach from here: Explaining economic growth is, in that research program, finding explanatory variables—technology or otherwise—that correlate strongly with (proxies for) A_j across countries. In effect the researcher writes ξ on the right of (3) as a function of particular observable economic or political variables. This research strategy underscores that while the original neoclassical model refers to A as technology or knowledge, no rigorous economic reasoning precludes A's being something else. In this paper, though, we concentrate exclusively on its original interpretation as technology.

2.3 Endogenizing technology

Kenneth Arrow's [6] model of learning by doing is widely viewed as the first rigorous attempt to endogenize technological progress $A/A = \xi$.

Interestingly, however, technical change in the model involves no deliberate economic decision. Instead, technical progress is an inadvertent consequence of yet other economic actions, in this case the act of investment. Incentives that affect investment affect, at the same time and in the same way, technological progress.

The model can therefore provide only an incomplete if useful first step. A different but related point: The model also describes an explicit economic environment generating from first principles a production function with externalities in capital (as used in, e.g., Romer [64]).

The model delivers an interesting set of implications:

1. The analogue of the production function (1) will show, under one interpretation, increasing returns to scale in K and N.

2. Nevertheless, compensation to the factors of production in decentralized markets will just exhaust total product.

3. Market equilibrium displays underinvestment relative to the socially efficient outcome.

4. Growth in y will, as in the neoclassical model, occur at the same rate as that in k and A. But A/A now is endogenous in that it depends on (part of the) economic environment, namely population growth. Significantly, however, incentives to capital investment do *not* affect the steady-state growth rate.

In the model suppose that technology is embodied entirely in physical capital, and that its level varies with the accumulation of all past investment activity. Simplify by assuming no depreciation (i.e., $\delta = 0$ in the notation above), so that accumulated investment is the same as the aggregate capital stock K.

From these assumptions technology levels can be indexed by $\kappa \in [0, K]$. Denote by $\mathcal{Y}(\kappa)$ and $\mathcal{N}(\kappa)$ the output capacity and labor requirements, respectively, of technology level κ, where

$$\mathcal{Y}' \geq 0 \quad \text{and} \quad \mathcal{N}' \leq 0. \tag{8}$$

With advances in technology, output capacities rise (or, more accurately, do not fall) and labor requirements fall. We have simplified by assuming that $\mathcal{Y}$ and $\mathcal{N}$ depend only on κ; no substitution possibilities are available. However, producers can choose not to operate specific technologies.

From (8) it is clear that if a certain technology κ is unused, then so are all technologies with indexes less than κ. Thus, there is a *shutdown threshold* $\underline{K} \in [0, K]$ such that no producer operates any technology with index less than $\underline{K}$. Define the integrals

$$\mathsf{Y}(K) = \int_0^K \mathcal{Y}(\kappa)\, d\kappa \quad \text{and} \quad \mathsf{N}(K) = \int_0^K \mathcal{N}(\kappa)\, d\kappa.$$

Aggregate output and employment are then

$$Y = \int_{\underline{K}}^{K} \mathcal{Y}(\kappa)\, d\kappa = \mathsf{Y}(K) - \mathsf{Y}(\underline{K})$$

$$N = \int_{\underline{K}}^{K} \mathcal{N}(\kappa)\, d\kappa = \mathsf{N}(K) - \mathsf{N}(\underline{K}).$$

Invert the last equation to solve for the shutdown threshold as a function of employment

$$\underline{K} = \mathsf{N}^{-1}\left(\mathsf{N}(K) - N\right).$$

Using this in the equation for aggregate output gives

$$Y = \mathsf{Y}(K) - \left(\mathsf{Y} \circ \mathsf{N}^{-1}\right)\left(\mathsf{N}(K) - N\right). \tag{9}$$

As Arrow [6] points out equation (9) is simply an aggregate production function in K and N. The novelty is that it has been derived from a more explicit microeconomic description incorporating, from the beginning, a formulation of technology.

Equation (9) can be rewritten in the form (1). To see this, it is easiest to work out an explicit example. Assume the functional forms for capacity and labor requirement:

$$\mathcal{Y}(\kappa) = \alpha \quad \text{and} \quad \mathcal{N}(\kappa) = \beta\kappa^{-\gamma}, \qquad \text{with } \alpha, \beta, \gamma > 0.$$

Using these in (9) and dividing through by N we have

$$y = \begin{cases} \left[1 - \left(1 - \frac{1-\gamma}{\beta}\frac{1}{k}K^{\gamma}\right)^{\frac{1}{1-\gamma}}\right]\alpha k & \text{if } \gamma \neq 1, \\ \left[1 - \left(e^{-1/k}\right)^{K/\beta}\right]\alpha k & \text{if } \gamma = 1. \end{cases}$$

Defining $A(K) = K^{\gamma}$, this is simply:

$$y = F(k, A) = \begin{cases} \left[1 - \left(1 - \frac{1-\gamma}{\beta}\frac{1}{k}A\right)^{\frac{1}{1-\gamma}}\right]\alpha k & \text{if } \gamma \neq 1, \\ \left[1 - \left(e^{-1/k}\right)^{A/\beta}\right]\alpha k & \text{if } \gamma = 1. \end{cases} \tag{10}$$

Inspection shows that equation (10) is homogeneous degree 1 in k and A and thus is covered by (1). When private agents take A in (10) as exogenously given, then this is, moreover, exactly the model specification used in Romer [64]. Conversely, taking into account that A depends on K we recognize that the production function (9) shows increasing returns in K and N.

Homogeneity of degree 1 in F implies that in balanced growth,

$$\dot{y}/y = k/k = A/A.$$

But by definition we also have

$$A/A = \gamma K/K.$$

Combining these relations, and provided that $\gamma < 1$, balanced growth occurs with

$$\dot{y}/y = A/A = \gamma K/K = \frac{\gamma}{1-\gamma}N/N. \tag{11}$$

Arrow [6] shows that: (a) compensation to labor and capital can occur sensibly despite increasing returns in (9); (b) competitive equilibrium exists and exhibits underinvestment relative to the social optimum. However, despite (b), steady-state growth rates are identical under both the competitive and socially efficient outcomes, as one would expect from the argument leading up to (11).

The model has of course endogenized technology A. Since steady-state growth, again, depends on technological progress, it too is similarly endogenous. However, that endogeneity leads only to a dependence on population growth as the determinant of growth. The analysis provides no positive message on the ability to improve economic growth through, say, encouraging capital investment. Indeed, such a policy would have no growth implications, only level ones—which could, of course, be substantial but are of less interest here.

2.4 Further endogenizing technology

The work of Aghion and Howitt [5], Grossman and Helpman [36], and Romer [65] are likely the best-known for providing explicit theoretical models of endogenous technological progress. Unlike the analysis discussed above, these models produce equilibria where the growth rate of technology is affected by economic incentives on capital accumulation or R&D or both. At the same time, their microeconomic implications are novel and interesting. The models display the tension between, on the one hand, policies that allow uncompetitive behavior on the supply side (incurring welfare losses in the process) so that, on the other hand, technical innovations and therefore economic growth are fostered.

As described in Jones [46] and Jones and Williams [47], these endogenous-technology models share a common structure. They all replace the technical progress equation (4) with a version of

$$A/A = G(R_A, A), \tag{12}$$

where R_A quantifies the resources—skilled labor, R&D spending, research scientists and engineers—devoted to improving technology, and A describes (the possible absence of) scale effects. In equilibrium, again, balanced growth arises so that $\dot{A}/A$ is then also the growth rate of per capita income or per worker output.

In the simplest versions of these models (12) is

$$\dot{A}/A = G(R_A) = R_A, \tag{13}$$

where, for instance as in Romer [65], R_A might be the total quantity of skilled labor working in the aggregate research sector. Here, modulo general equilibrium effects, providing incentives for the skilled to move into research improves the rate of economic growth.

Jones [46] argues forcefully against models of endogenous technical progress of the form (13). He observes for the advanced economies that while every reasonable measure of R_A has increased dramatically in the last half century, per capita income growth rates have either remained roughly constant or even declined. For example, US scientists and engineers employed in R&D increased five-fold from 1950 and 1990; average US growth rates did nothing anywhere near this.[7]

Function G in (13) need not, of course, be linear in R_A. However, almost all models of endogenous technical change (and certainly those of Aghion and Howitt [5], Grossman and Helpman [36], and Romer [65]) yield that linearity from explicit microfoundations. Jones [46] labels this a *scale effect*, and argues that it is this feature that empirically invalidates these models.

Jones's preferred alternative specification obtains instead from the following reasoning. Identify A as the stock of ideas, and suppose that

$$A = \tilde{\rho} R_A^{\theta}, \qquad \theta \in (0, 1],$$

i.e., the flow of new ideas varies with the quantity of resources devoted to research. The factor $\tilde{\rho}$ can be interpreted as the arrival rate of new ideas

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[7] Jones [46] and Aghion and Howitt [4], among others, point out that the increase in R&D investment was possibly not as high as the data suggest. After the Second World War as R&D activities became increasingly routine and separately accounted for, their measured resource use increased regardless of any real resource increase. The scale effects predicted in some endogenous growth models might therefore not be as unreasonable as initially thought.

per effective research unit. When $\theta = 1$, an effective research unit is just the same as an observed research unit. When $\theta < 1$, however, research units can be viewed as congested: There might be, for instance, overlap between projects run by different researchers. (e.g., Dasgupta and Maskin [20]).

The arrival rate $\tilde{\rho}$ depends, in turn, on the stock of ideas already extant:

$$\tilde{\rho} = \rho A^{\phi}, \qquad \rho > 0,\ \phi \in (-\infty, \infty).$$

When $\phi < 0$, the stock of ideas outstanding has begun to run out; when $\phi > 0$, ideas build on other ideas already discovered.

Putting these together gives the specification in Jones [46] and Jones and Williams [47]:

$$A/A = G(R_A, A) = \rho R_A^{\theta} A^{\phi-1}. \tag{14}$$

Standard *scale effects* obtain when $\theta = \phi = 1$.

When $\phi < 1$, scale effects are no longer present; since ϕ can be positive, ideas can still build on ideas extant. However, (14) then implies growth dynamics that only mimic (11) in Arrow's model of learning by doing. In balanced growth, R_A^{θ} and $A^{1-\phi}$ grow at the same rate so that

$$A/A = \frac{\theta}{1-\phi} R_A/R_A.$$

When R_A evolves in constant proportion to the population or the labor work force, then this is exactly (11), the growth equation in Arrow's model of learning by doing.

2.5 Some outstanding issues

Although not emphasized above, some of (in our view) the most interesting economic issues surrounding technological development relate to the peculiar characteristics of knowledge when viewed as an economic commodity. Emphasizing knowledge as the critical factor input in economic growth while at the same time recognizing the importance of incentives cannot but raise questions regarding property rights on knowledge.

The intriguing properties of knowledge as property were first observed in the formal economics literature in a different 1962 publication of Arrow's (Arrow [7]).[8] More recently, Romer [65] has used them to argue for the necessity of imperfect competition (and transient monopolies) in models of endogenous technology and growth, a Schumpeterian view shared also by the models in Aghion and Howitt [5] and Grossman and Helpman [36].

The argument goes as follows. Knowledge and ideas are infinitely expansible (or nonrival)—unlike physical material factor inputs they can be used arbitrarily everywhere without running down their usefulness in any one place or at any one application.[9] Applying the usual replication argument to standard capital and labor factor inputs, the production function therefore displays increasing returns. Then, perfectly competitive markets and marginal product compensation to factor inputs would more than exhaust total output. An element of monopoly or other market imperfection circumvents this potential failure, is necessary to allow sensible market equilibrium, and, moreover, generates rent to support research activity.

Equilibrium with these features can be supported by a patents system or some other structure that protects intellectual property rights. Despite the ex post inefficiencies that such systems generate, they provide the ex ante economic incentives to allow ongoing generation of ideas and thus technological progress.

We do not disagree with the motivating observations on knowledge as economic objects given in Arrow [7]. Indeed, we think those insights assume increasing relevance as modern economies grow and structurally transform.[10] However, we think there has been over-emphasis here on the supply side of the economy, i.e., technology only to push back the frontiers of the production function. Instead the consumption and dissemination aspects of new technology are arguably just as important, and the factors that matter here

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[8] Paul David points out to us that a letter of Thomas Jefferson's on the *infinite expansibility* of ideas is an even earlier if nontechnical source of these observations; see Koch and Peden [52, 629–630].

[9] We say "infinite expansibility" rather than "nonrivalry"—they have the same meaning—because the positive term seems to us more descriptive and thus more useful than a negation (non$X$ just means everything but X).

[10] See for instance Quah [61].

need not be as strongly tied to the usual systems of intellectual property rights.

Researchers in the economics of science and knowledge have long studied the impact on economic efficiency of alternative definitions of what it means to own and disclose a piece of knowledge. Dasgupta and David [19], David [21, 22], Scotchmer [69], and Wright [76] are recent examples. The patent system, a standard formalization of intellectual property rights in endogenous growth theory, is but one of several possibilities.

A first and likely the best-known of these is the system of patents. A patent system grants monopoly rights, for a definite time length, to the original creator or her agents to allow exclusive ownership and thus rent extraction from that idea or discovery. Although legally distinct, copyrights, trade secrets, and design rights (see, e.g., Holyoak and Torremans [42]) can all be lumped together with patents, and as a group constitute intellectual property proper.

A second system is one of publicly-financed prizes or research grants awarded for proposals judged in competition with others. Following a one-time reward the knowledge becomes public property and can be freely used by all agents in the economy.

A third system is where a public body contracts out in advance for a piece of research to be undertaken. The findings from that research are typically understood to be, again, available to all agents in the economy, although this varies.

Reality contains few pure examples of these three possibilities, but taken together they constitute a useful taxonomy.[11] Patent systems in different countries constitute versions of the first category. The second category includes, say, academic research financed by the NSF in the US or the ESRC in the UK. An example of the third would be military research. When the research output goes directly into the public good called national defense, benefits do accrue to all in the economy. The findings of military research, however, are not usually available in any detail except perhaps in some mutated form.[12] Both the second and third systems of idea creation would, in

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[11] David [21] calls these, respectively, the 3 P's: Property, Patronage, and Procurement.

[12] A different example of the third—of intellectual property in general

general, be financed from general taxation.

Wright [76] studies the efficiency properties of the three alternative systems. Based on typical structures of individual firms' private information, one would generally expect the patents system to be superior for its emphasis on individual incentives. Wright [76] shows that this intuition can be misleading, and that in many cases patronage and procurement might well dominate patents for producing social efficiency. The principal reason is the social externality costs in researchers working on closely related problems.

Similarly, Scotchmer [69] shows that even confining attention to the patent system, once one takes into account the cumulative nature of research—that discoveries build on earlier discoveries—the patent system is severely limited in being able to finetune appropriate incentives for efficient outcomes. Scotchmer too argues for greater reliance on patronage and procurement.

These subtleties in alternative systems of intellectual property rights have not yet been fully incorporated in analyses of endogenous growth. This area of research seems to us potentially quite fruitful.

Scotchmer's analysis of economic agents' subsequently using an initial discovery by a yet different agent is an example of the *demand side* of the market for ideas. The comparison to draw is with the supply side generating those ideas. In one interpretation, all the endogenous growth models we reviewed above focus only on the latter. Helpman [40], by contrast, considers a model of innovation and imitation, where advanced and developing economies are explicitly identified. In Helpman's dynamic general equilibrium analysis with endogenous innovation, relaxing control over intellectual property rights can be welfare-improving for all. That economic welfare rises is obvious for the economies doing the imitation. For those economies engaged in innovation, the general equilibrium consequences of having a faster growing, more productive rest of the world can outweigh the welfare losses from detrimental changes in terms of trade and the shift in patterns of innovation.

Acknowledging R&D as an engine of growth but, at the same time, recognizing the significance of incentives highlights the importance of the economics of knowledge. It is useful then to note that Arrow's observations on

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although not research in the narrow sense—might be royal patronage to support the musical creations of a Bach or Mozart. This example overlaps also with the second category.

knowledge do not end with just infinite expansibility or nonrivalry. Knowledge is also differentially and asymetrically known, involves setup costs in use, and displays priority significance (the time series counterpart of the winner-take-all Superstar behavior in cross section studied in Rosen [67]). Quah [62] has used these observations to analyze further the demand side of the market in knowledge. Moreover, since computer software and many other elements of the fast-growing weightless economy (Quah [61]) share properties in common with knowledge, such analysis takes on increased empirical relevance, not just for understanding R&D and economic growth in particular, but economic performance in general.

3 Empirical studies: R&D and the impact of property rights on growth

Underlying the idea creation in (14) is a description of how profit-maximising firms willingly generate infinitely expansible ideas. Explicit examples of such mechanisms are in Aghion and Howitt [5], Grossman and Helpman [36], Jones [46], and Romer [65]).

The basic insight is that firms agree to devote resources R_A to create new knowledge because their contributions to (part of) A/A can be guaranteed by intellectual property rights. As Section 2 suggests, we are mindful of the subtleties here. However, following most endogenous growth analyses, we proceed by taking such rights to be described by patents. Viewed thus, equation (14) embeds three key features:

1. The relation between R_A and A/A whereby patented technology is an input into the production function;

2. The uni-dimensionality of technology where it is only the aggregate patented stock of knowledge A that matters;

3. The public availability of A for research, even if it is protected for owner use in production.

Several strands in the empirical literature on patents, R&D, and growth can help in evaluating 1.–3. We sacrifice completeness for conciseness in describing the many important pieces of research done in this area. Where empirical findings importantly contradict theoretical assumptions, we suggest ways to address these inconsistencies in future research.

We find that empirical work partly confirms 1. and 3. Empirical research suggests 2. is inadequate.

3.1 Resources and increases in knowledge

Begin by considering tests of the relation between knowledge inputs proxied by R&D and outputs proxied by patents. A huge empirical literature developed in the 1980s on the relation between patents, R&D, and individual firm performance (Griliches [35] and Keely [49] provide surveys).

Three main results emerge from this literature. First, private sector patents and R&D are strongly related only contemporaneously (Griliches, Hall, and Hausman [38, 39]). This result contradicts the intuition that there ought to be a dynamic lagged relation between R&D inputs and outputs. However, Jaffe [43] has provided evidence that patenting occurs very early in the research process, while Pakes [59] shows that past R&D does have an effect on current patenting.

Second, patents help explain Tobin's q and total factor productivity (TFP) in firms, and R&D effects tend to be much larger and therefore more important for firm performance than for the aggregate economy (Cockburn and Griliches [14], Hall [37], and Megna and Klock [58]). The distribution of patent values is highly skewed; most patents are essentially worthless (Schankerman [68]). When quality-weighted with citation data, patent counts have higher explanatory power (compared to unweighted counts) for individual firm performance (Hall [37]). However, R&D almost always remains the more significant explanatory variable. These results make it doubtful that patents accurately or meaningfully proxy knowledge output.

Third, this research points to the productivity slowdown in advanced economies. In the United States the patent/R&D ratio has markedly declined over the last 30 years. At least three explanations have been given for this: (i) exhaustion of research potential (Evenson [27, 28]); (ii) expansion of markets leading to increased R&D competition and activity (Kortum [53]); and

(iii) decrease in the propensity to patent (Griliches [34] and Kortum [53]).[13] Explanation (i) seems to us incomplete because if research opportunities have decreased, so should R&D investment decline. There need be no unambiguous effect on the patent/R&D ratio. Kortum [53] examined explanation (ii), but found insufficient demand growth to explain the increase in R&D activity. Griliches proposed that a decrease in the propensity to patent was due to an increase in bureaucratic costs of patenting. A related explanation for such a decline would be a change in the mix of innovations whereby fewer inventions are patentable (Gittleman and Wolff [31] and Keely [49]).

To summarize, the data show correlations between individual firm R&D and patents, and between both R&D and patents on the one hand and firm performance measures on the other. The nature of these correlations is, however, (acknowledged to be) ill understood. Moreover, the patent/R&D correlation has been recently negative without conclusive corroborating evidence that innovation productivity has fallen. Thus, while final conclusions remain outstanding, a preliminary suggestion—one to which we are sympathetic—is that patents do not at all do a good job of describing the effects of innovation on economic performance.

3.2 Significance of aggregate patented knowledge

Turn now to 2.: The knowledge stock that matters for rent appropriation is the aggregate of patented outputs from private-sector R&D.

Perhaps the most important information on this is the survey summarized in Levin, Klevorick, Nelson, and Winter [54]. The main conclusions of this survey are well-known and will only be briefly re-stated here. Patents were found to be a significant form of rent appropriation in only a few industries: drugs, plastic materials, inorganic chemicals, organic chemicals, and petroleum refining. Overall, however, product and process patents were found to be less effective than any other form of protection or appropriation. Those alternative forms were identified to be secrecy, lead time, moving down the learning curve, and sales or service. Deemed most important were the second and third of these, most usefully viewed, perhaps, as simply learning

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[13] Soete [70] summarizes discussions of mismeasurement and short-termism in R&D choice.

effects.

The results from this survey cast doubt on the usefulness of the private R&D/patenting paradigm as well as that of of endogenous growth models with perfect learning spillovers across firms. Altering these models to be consistent with these survey results seems to us a valuable enterprise, but the implications of doing so have not yet been fully explored.

It is not just profit-maximizing firms that perform R&D. Government and universities do so too. Government-funded R&D constitutes one-third to one-half of total R&D expenditures in the United States and several countries of Europe (Feldman and Lichtenberg [29] and National Science Foundation 1996 [30]).[14] This type of R&D is sometimes called "basic research" although it is likely not research content that differs so much as the incentives of the scientists involved (Dasgupta and David [18, 19]). Academic and government scientists do not work for profit-maximizing firms. Their incentives will not be to patent innovations for appropriating rent, but rather to disclose new knowledge in order to receive rewards associated with priority. Adams [2], Griliches [33], and Mansfield [57], among others, have documented the positive correlation between individual firms' "basic research" and their productivity growth. More recent work (e.g., Adams and Griliches [3], Cockburn and Henderson [15], Henderson, Jaffe, and Trajtenberg [41], Pavitt [60], and Zucker, Darby, and Torero [77]) find evidence of knowledge spillovers between private and academic science. This work documents the positive effects of these interactions on firm productivity.

The typical explanation for ignoring public R&D in endogenous growth models is that such R&D must be subsidized and is freely available. Therefore "the economics of this type of knowledge are relatively straightforward" (D. Romer [63]). However, empirical work described above as well as theoretical models in industrial organization (e.g., Dasgupta [17] and Dasgupta and Maskin [20]) indicate the effects of basic scientific research on economic growth could well be important. Nor does the economic theory for understanding basic science seem, to us, at all straightforward.

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[14] The 1996 figures are: 34% United States, 32% United Kingdom, 37% Germany, and about 45% in France and Italy.

3.3 Dissemination and spillovers

Feature 3. in R&D endogenous growth says the knowledge stock is available to all potential inventors for further research. As noted in Section 2, when discussing the neoclassical growth mechanism, equations (1) and (4) in particular, there is no good reason to presume that A or $\dot{A}/A$ are the same across countries or even within countries. In different form, it is this same issue that arises for endogenous growth when one examines 3.

We consider the empirical evidence in two steps. First, we look at micro- and macro-economic evidence on whether such spillovers exist across economic agents. Second, we examine evidence on how large such spillovers are, to see how much the same knowledge stock is available to all. We will conclude that spillovers of knowledge do occur across agents and affect their productivity, but the spillovers are not uniform across physical and technological locations.

Microeconomic evidence on physical clustering of innovative activity is remarkably consistent across studies. Ciccone and Hall [13] conclude that employment density increases labor productivity, supporting therefore the view that knowledge spillovers occur across workers in the same location. Audretsch and Feldman [8] find that, even after controlling for production density, industries where knowledge is a significant input in production tend physically to cluster innovations more than do other industries. Similarly, Jaffe and Trajtenberg [44] and Jaffe, Trajtenberg, and Henderson [45] show that geographical proximity increases patent citations between institutions, again controlling for production density within industries. Finally, apart from physical location, a given firm's R&D productivity increases with the R&D performed by all firms in the same industry, even though the individual firm's profitability might suffer (Jaffe [43]).

We conclude from this evidence that knowledge spillovers do occur. However, the physical clustering of innovation suggests that spillovers do not happen automatically or completely.

Macroeconomic evidence too supports the hypothesis of knowledge spillovers, although their extent and completeness remain unclear. Much of the empirical research looks for spillovers in international data. In one interpretation, many R&D endogenous growth models are closed-economy ones and thus are silent on the issue of international diffusion. But significant exceptions exist, e.g., the models in Barro and Sala-i-Martin [10], Grossman and Helpman [36], and Helpman [40].

In an example of seeking knowledge spillovers within a macroeconomy, Caballero and Jaffe [12] use U.S. patent and citation data to calibrate a model of creative destruction and endogenous technological obsolescence and diffusion. They estimate that diffusion of knowledge from patents occurs with a mean lag of 1–2 years, but that the decrease over the 20th century in patent citation rate indicates a fall in the strength of those spillovers. The result is a decline in growth of the public knowledge stock.

More studies are available on R&D spillovers from advanced to developing countries. Coe, Helpman, and Hoffmeister [16] document evidence of spillovers via TFP effects in developing countries. They find that TFP in a typical developing country increases with a rise in the country's trade openness, its average rate of secondary school enrollment, its import share from advanced economies, and its import share of GDP. The effect of the foreign R&D stock is strong but significant only when interacted with the import share variable. This finding supports the view that knowledge spillovers occur only via a specific channel of economic interaction such as trade or migration.

Bayoumi, Coe, and Helpman [11] build on that earlier work in a model of R&D, spillovers, and endogenous growth, where R&D spillovers occur through imports. In both papers, R&D influences growth through TFP and capital accumulation. Simulations support the model as an empirically accurate description of cross-country patterns of growth.

Another way to examine imperfect knowledge spillovers uses cross-country regressions with the dependent variable being either own-country R&D (Gittleman and Wolff [31]) or own-country intellectual property rights protection (Gould and Gruben [32]). When any one country's R&D stock or flow is small relative to the entire world's, then a significant effect of own R&D in such a cross-country regression indicates that knowledge spillovers are incomplete. Gittleman and Wolff [31] find that own R&D is insignificant in the regression with all countries included. However, in subsamples chosen by income levels, the regression coefficient is positive for upper and middle income countries (where almost all R&D occurs). Cross-country spillovers therefore do occur but are incomplete.[15]

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[15] Gould and Gruben [32] also report a positive and significant effect of

In a series of papers, Eaton and Kortum [24-26] develop and calibrate a model of R&D, patenting, knowledge diffusion, and growth to estimate the impact of foreign technology on productivity growth. They examine the hypothesis that foreign technology is difficult to adopt. Productivity levels in the model are affected by the ability to innovate domestically and the readiness to adopt foreign technologies. Therefore, although steady state income growth rates converge to the same level, productivity level differences persist across countries. Calibrations show consistency with actual growth experiences of different countries. The bulk of technology growth is estimated to originate in the U.S, Germany, and Japan.

To summarize, despite the differences in methodologies and emphases in the studies above, the broad conclusion is that spillovers across regions do occur. At the same time, however, these spillovers are generally incomplete.

3.4 Extensions

As discussed in Section 2, Jones [46] has forcefully criticized R&D-driven endogenous growth models by documenting their empirical failure on scale effects. The revision, suggested by Jones [46], posits that research effort duplication could produce decreasing returns in the measured resources devoted to R&D.

The spillovers results we have just reviewed suggest another possibility. Although knowledge is in principle infinitely expansible, there might be significant obstacles to its widespread use, even aside from protection in intellectual property rights. Examples that we have in mind given our review of the evidence include the lack of contact between scientists in different physical or technological areas, and the absence of an infrastructure to introduce and utilize new products or processes.

Therefore, a fruitful area of research is to identify the mechanisms by which economic interactions lead to knowledge spillovers. Understanding

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intellectual property right protection on GDP growth. This confirms the hypothesized importance of incentives for accumulating knowledge and promoting growth, a view which this paper maintains. The finding does not say, however, that other less obvious forms of knowledge protection and dissemination might not also be important.

such mechanisms would aid policy formulation when knowledge spillovers are an important channel for economic growth. In other words, it might be useful to increase research emphasis on the use and dissemination of knowledge on the demand side, not just study legal institutions on the supply side that induce innovation in profit-maximizing firms. Also of interest would be to understand mechanisms whereby researchers in non-market environments create and disclose new ideas (e.g., Keely [50] and Weitzman [75]).

These two—dissemination on the demand side of the market for knowledge and non-market institutions on the supply side—might well have effects on economic growth that dominate the factors endogenous growth theory traditionally studies.

4 Conclusions

This paper has reviewed the development of R&D endogenous growth theory, tracing the close relationship between earlier and more recent literatures. The paper has compared that theoretical paradigm with empirical evidence on the formation and diffusion of new ideas.

A consistent picture emerges. Economic theory emphasizes the importance for growth of incentives in the production of useful knowledge, and, more generally, the significance of intellectual property rights. The framework of private-sector R&D as input and intellectual property as output clarifies those incentives for innovation by profit-maximizing firms. This view is one that sees some empirical support in economic data.

However, this framework is an incomplete one for understanding economic growth and the process of idea creation.

First, it is not just private sector, profit-maximizing firms that generate the bulk of useful knowledge. Governments and academics do so as well. Incentive structures in this broader nonmarket context are subtle but no less important for economic growth.

Second, it is not just patents that provide property rights to knowledge. Alternative structures that do so are arguably more important in reality, and moreover provide incentive and efficiency implications that differ profoundly from those of a patent system.

These extensions and complications have yet to be incorporated into models of R&D and endogenous growth. The payoffs to doing so are likely high for understanding the effects of policy on growth.

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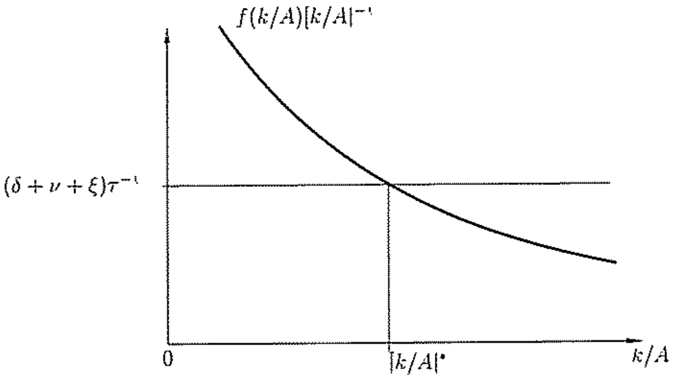

Fig. 1: Neoclassical growth and convergence The function $f(\tilde{k})\tilde{k}^{-1}$ is continuous, and tends to infinity and zero as $\tilde{k}$ tends to zero and infinity, respectively. Moreover, it is guaranteed to be monotone strictly decreasing. The vertical distance between $f(k/A)[k/A]^{-1}$ and $(\delta+\nu+\xi)\tau^{-1}$ is $\tau^{-1}[k/A]/[k/A]$. Convergence to steady state $[k/A]^*$ therefore occurs for all initial values k/A.

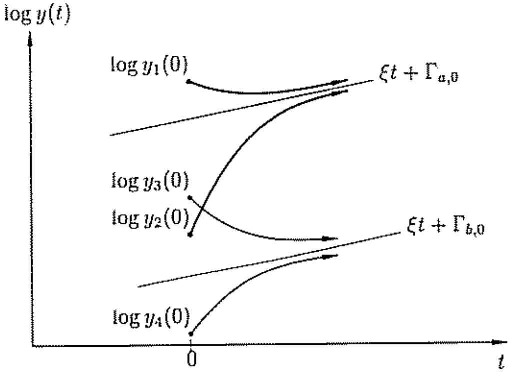

Fig. 2: Growth and convergence in the neoclassical model Figure shows two different possible steady state paths—corresponding to two possible values for $\Gamma_{j,0} = g((\delta + \nu_j + \xi_j)^{-1}\tau_j) + \log A_j(0)$. As long as this remains unobserved or unrestricted, *any* pattern of cross-country growth and convergence is consistent with the model. As drawn, the a value applies to economies at $y_1(0)$ and $y_2(0)$ while the b value to $y_3(0)$ and $y_4(0)$. Economies 1 and 2 converge towards each other, and similarly economies 3 and 4. At the same time, however, economies 2 and 3, although each obeying the neoclassical growth model, are seen to approach one another, criss-cross, and then to diverge.